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CONSIDERATIONS FOR SPACE AND NAVAL AIRCRAFT APPLICATIONS OF FERROELECTRIC MEMORY

by
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Lieutenant, United States Navy
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Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS TECHNOLOGY,
SPACE SYSTEMS OPERATIONS

from the

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December 1992

ABSTRACT

The purpose of this thesis is to introduce the reader to Ferroelectric memory and discuss considerations for possible space and Naval aviation applications. Ferroelectric memory's characteristics and basic mechanism are discussed. A broad spectrum of existing computer memory types are presented for comparison. The memory requirements of Space Shuttle, Landsat, Intelsat V and Hubble Space telescope as well as the Navy E-2 Hawkeye and EA-6B Prowler aircraft are given as examples of possible space and Naval aviation applications of ferroelectric memory.

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I. INTRODUCTION

The purpose of this thesis is to introduce the reader to FerroElectric Memory (FEM) and discuss possible space and Naval aviation applications of this promising technology. FEM is a new type of semiconductor computer memory based manufactured with ferroelectric materials. It is referred to as Ferroelectric Random Access Memory (FRAM®--Ramtron registered trade name) or FERroelectric Random Access Memory (FERRAM) by companies and agencies researching and developing FEM. Ferroelectric memories have several desirable attributes including non-volatility, low power, high speed, small size, high memory capacity and inherent radiation hardness. This thesis will also discuss some existing forms of space and aviation computer memory as possible applications of FEM.

A. PRINCIPLES OF FERROELECTRIC MEMORY

1. General Description

FEM semiconductor chips utilize a thin film of ferroelectric material as the dielectric capacitor material. They are similar in design and overall function to Dynamic Random Access Memory (DRAM) chips. A ferroelectric material has the ability to shift between two polarization states based on the orientation of an applied electric field and then maintain the polarization state present before the field is removed. Therefore, FEM actually stores binary data in the polarization state of the ferroelectric material itself (Josefson, 1990, p.1). This chapter will discuss characteristics of ferroelectric based computer memory.

Ferroelectric properties have been found in several compounds including barium titanate and lead-zirconate-titanate. The most promising results have been attained with Lead-Zirconate-Titanate (also known as PZT) and a yet undisclosed Symetrix substance designated as "Y1". Both of the compounds are formed of unit cells with a cube-like structure named Perovskite after Count L. A. Perovski who discovered them (Wight, 1990, p.12).

2. Perovskite Unit Cell Structure and Binary Data

Figure 1 shows two perovskite unit cells and the two possible stable positions for the unit cell's central atom (designated as "B"). The two stable positions can be directly correlated to binary data. For instance, "one" could be assigned to the top position and "zero" to the bottom position.

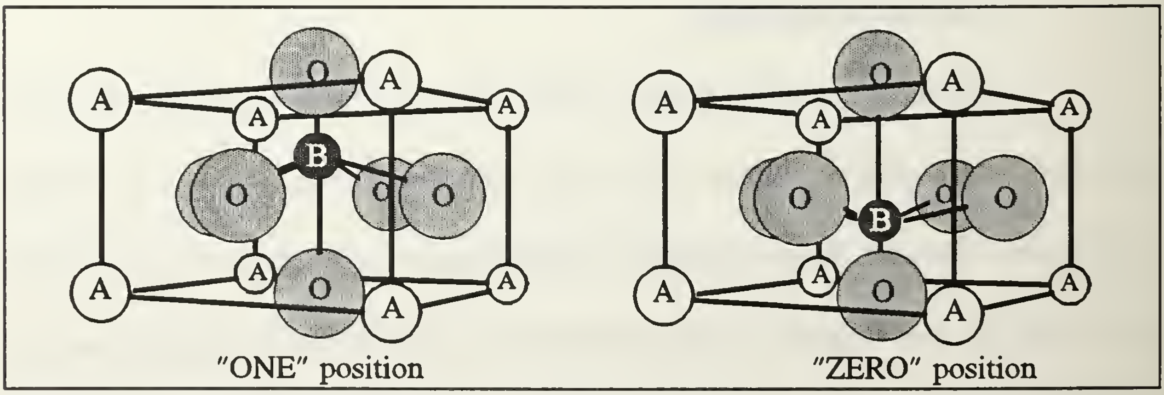


Figure 1. Perovskite Unit Cells

An electric field occurs when there is a difference in electric potential between two plates of a capacitor. If a positive voltage is applied to the top plate and a negative voltage to the bottom plate, then a "positive" electric field will arise pointing from the bottom plate toward the top plate.

In the unit cell, the "B" atom can be toggled between the two stable positions by applying an external electric field across the ferroelectric material pointing toward the cell's top or bottom. For example, to write a "one", an electric field is applied pointing towards the top of the unit cell. When the electric field is removed, the "B" atom remains in the top "one" position held by molecular forces. When an electric field is applied pointing toward the bottom of the unit cell, the "B" atom toggles to the bottom "zero" position and remains there.

During the manufacturing process, the thin film of ferroelectric material can be aligned so that the unit cell's stable positions are aligned nearest to the upper surface and lower base of the film in a process called annealing. Figure 2 shows a simple FEM memory cell. The resulting electric field across the ferroelectric layer (between the top and bottom capacitor plates) would toggle the "B" atoms in the unit cells.

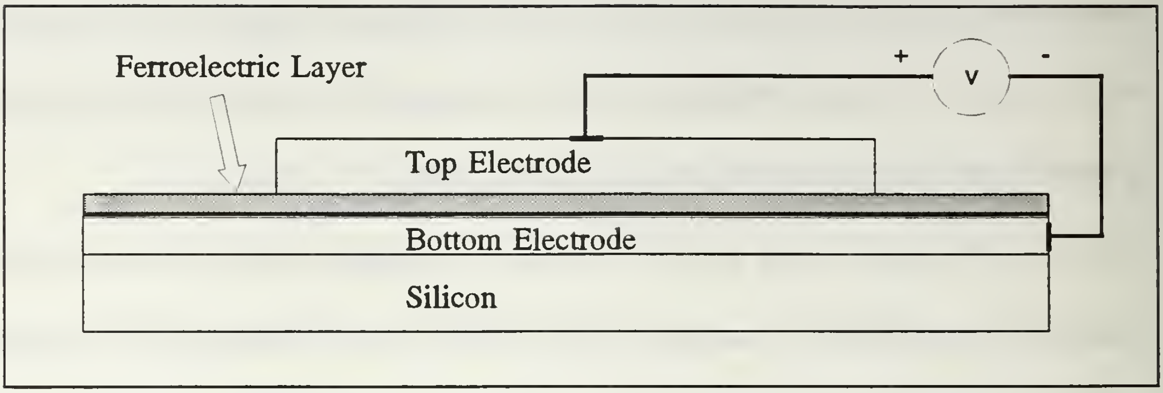


Figure 2. Simple FEM Capacitor

3. Graphical Description of FEM Binary Data Storage

a. Polarization vs Electric Field

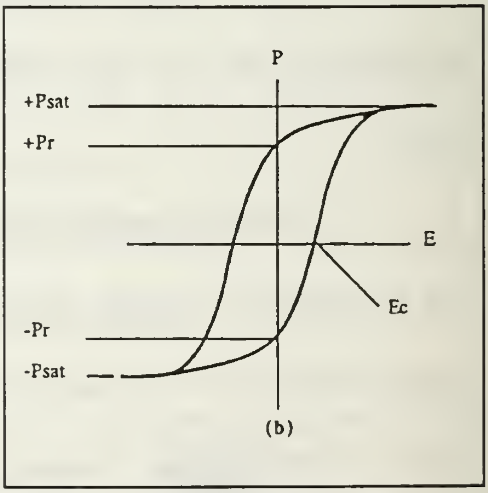


Figure 3. FEM Hysteresis Loop

The process of storing binary data in the perovskite unit cells can be described graphically with the hysteresis loop shown in Figure 3 (Josefson, 1990, p.9). The vertical axis is polarization (P) and the horizontal axis is applied electric field (E). The $+P_r$ represents the "one" position and $-P_r$ represents the "zero" position. Characteristics of the hysteresis loop will be described next.

b. Positive Saturation Polarization (+P_{sat})

Figure 4 depicts positive saturation polarization (+P_{sat}) that is attained when a full positive electric field is applied across the ferroelectric layer pointing toward the surface of the unit cells. This results from applying +5 volts to the top plate of the capacitor. The central atom toggles to the top of the unit cells in response. +P_{sat} will remain as long as the positive voltage is applied.

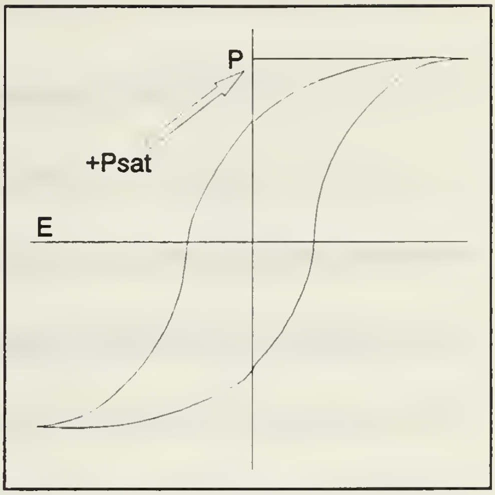


Figure 4. Positive Saturation Polarization

c. Positive Remnant Polarization (+P_r)

Figure 5 shows the level of positive polarization remaining after the positive electric field is removed. Positive remnant polarization (+P_r) represents the binary "one" stable position. A simple analogy to the stable position would be bowling ball in the left gutter of a bowling lane. The ball would not be able to get to the right gutter unless someone physically lifted it out and rolled it to the other side.

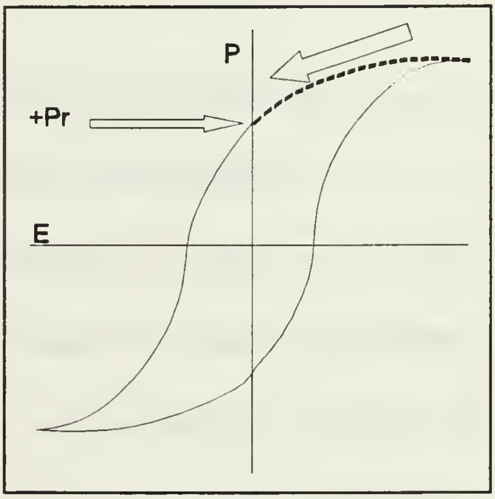


Figure 5. Positive Remnant Polarization

Due to the molecular forces holding it in position, the central atom is unable to switch positions without the external force of an applied negative electric field.

d. Negative Saturation Polarization ($-P_{sat}$)

Figure 6 shows negative saturation polarization ($-P_{sat}$), the polarization state attained by applying a negative electric field across the ferroelectric layer pointing toward the base of the unit cells as the result of +5 volts being applied to the bottom capacitor. The $-P_{sat}$ state will remain as long as the negative field is applied.

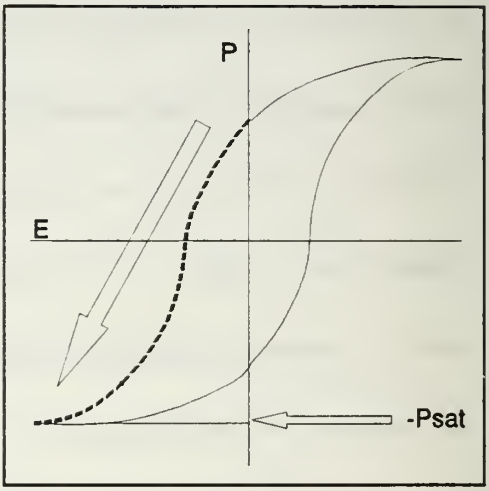


Figure 6. Negative Saturation Polarization

e. Negative Remnant Polarization ($-P_r$)

Figure 7 represents negative remnant polarization ($-P_r$) that remains when the negative electric field is removed. A binary "zero" has now been written. In the absence of an applied electric field, the "B" atoms will remain in this position indefinitely.

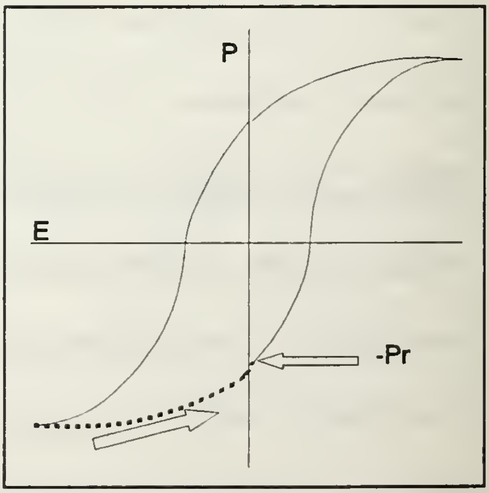


Figure 7. Negative Remnant Polarization

B. DESIRABLE CHARACTERISTICS OF FERROELECTRIC MEMORY

1. Non-Volatility

A volatile memory loses the data stored in it when power is removed. Volatile memories include Dynamic Random Access Memories (DRAMs) and Static Random Access Memories (SRAMs). Non-volatile memories include core, plated wire, bubble, magnetic tape and magnetic disk memories. (Chapter Two discusses these memory types.) FEM does not require power to maintain data since information is stored as distinct atom positions which are held in place by molecular forces. Currently, FEM researchers agree that data can be maintained without power for a minimum of 10 years (Messenger, 1988, p. 1461 / Bondurant, 1992, phone conversation / Wrobel, 1987, p.1).

2. Insensitivity to Magnetic Field

Since the mechanism of FEM data storage is molecular attractive-repulsive forces, data is not affected by magnetic fields. The only way that the central atoms can change position is under the influence of an applied electric field. Magnetic fields do not affect the unit cell molecular forces. Magnetic tapes and disks are two examples of memory that can be altered or damaged by magnetic fields.

3. Radiation Hardness

Since data is held in place by molecular forces, FEM is inherently radiation hard to Single Event Upsets (SEUs) and memory cell damage without shielding (Scott et al, 1989, p.1444 / Wrobel et al, 1987, p.3). Gamma radiation, high energy particles or neutrons would have to physically hit and displace individual atoms in a unit cell in order to affect its polarization state. The smallest FEM cell theoretically possible (due to dielectric constant constraints) is $2\mu \times 2\mu \times 0.2\mu = 8 \times 10^{-19}\ m^3$ (Araujo, 1992, phone conversation). It is estimated that each perovskite unit cell is about 3 angstroms wide (Bondurant, 1992, p.1). This would result in $\sim 2.69 \times 10^{10}$ unit cells per memory cell. If some atoms were hit and their positions changed, the memory cell's *overall* polarization would not change. It has been estimated that the minimum P_r needed for a FEM device to distinguish between polarization states is $0.5\ \mu C/cm^2$ (Fisch et al, 1990, p.239).

Several ferroelectric devices have been tested for SEU and radiation damage hardness. Table I shows some FEM radiation hardness test results. No ferroelectric devices showed SEU. A few non-PZT and some PZT devices made by Krysalis showed permanent damage under shorted test conditions. Ramtron FRAM® chips have been proven Single Event Upset (SEU) equivalent to radiation hardened SRAM chips (Bondurant, 1992, phone conversation).

Table I. FERROELECTRIC DEVICE RADIATION TEST RESULTS

Test Object	Test condition	X-ray Dose Rate	X-ray Total Dose	Heavy Ion Dose	SEU	P_r Loss	Reference
Krysalis Test Capacitors	AC bias	1.2 x 10^{11} rad(si)/s	4.5 x 10^6 rad(si)	NA	none	60% due to 10^{12} cycle fatigue	Wrobel et al, 1988, p.3-4
	shorted	1.2 x 10^{11}	3600	NA	none	none	
	DC bias	NA	NA	6 x 10^6	none	none	
	shorted	NA	NA	8 x 10^6	none	none	
Krysalys 1987 devices	shorted / open	NA	NA	16 x 10^6 ions / cm^2 (1.1 MEV Co^{60})	none	Fail @ 10 x 10^6 rad	Schwank et al, 1990, p.1705
National Semi & Sandia Labs 1989 devices	shorted / open				none	Sandia: 10 % -30% National: 20%	p. 1707
KNO^3 test device (4 samples)	unreported	NA	NA	0.5 x 10^6 rad 1.1 MEV Co^{60}	none	12%, 50%, 90% and one complete failure	Scott et al(1) 1989, p.1444-6
PZT test devices	shorted	NA	NA	5 x 10^6 rad ((1.1 MEV) Co^{60})	none	2/8 failed 6/8: 14%	p.1449
	AC bias				none	17.5%	p.1449
	open				none	unreported	NA
	shorted	2.6 x 10^{11} rad / s	2600 rad	NA	none	2/4: 10% 2/4:10%	p.1450
	DC bias				none	+ 5%	
	open				none	6.7%	
Own Lab PZT capacitors	open	NA	NA	0.62 x 10^6 rad(si)	none	~25%	Lee et al, 1992, p.1-4
512 bit test chip	unreported	1.2 x 10^{11} rad(si)/s	10^7	NA	none	none	Messenger, 1988, p.1461 - 1466
		NA	NA	6 x 10^6	none	none	

Standard semiconductor chips are manufactured from non-radiation hardened materials. Since the ferroelectric material is radiation hard, ferroelectric semiconductor chips would be as radiation hard as the other materials used in manufacturing the chip. Wrobel and Schwank describe ferroelectric radiation hardness potential in the following quotes:

> It can be seen from the data presented, that ferroelectric capacitors have very high tolerance to total dose and dose-rate radiation environments. These capacitors merged with radiation hardened CMOS decoding circuitry, should produce a non-volatile RAM limited only by the CMOS hardness. (Wrobel, 1988, p. 4)
>
> The small degradation in R ($\sim 2\ P_r$) for the Sandia and National capacitors indicates that, if the associated circuitry on a ferroelectric memory can be radiation hardened to present day levels of radiation hardness, then ferroelectric memories can be fabricated that will survive dose levels in excess of 10×10^6 rad(si). (Schwank, 1990, p. 1710)

a. Environmental Radiation

Environmental and cosmic radiation consists of high energy particles from solar flares, Van Allen radiation belts and galactic cosmic rays (Mc Donald, 1992, p. 26). This type of radiation causes SEU and slow degradation in standard semiconductor memory devices.

As shown in Table I, FEM test devices have shown substantial radiation hardness. Heavy ion bombardment up to 10^{15} n/cm^2 have damaged some PZT devices under short circuit conditions and devices made by Krysalis under all conditions. Other devices have performed well in heavy ion tests in all conditions.

The theoretical displacement damage threshold for FEM devices is 5×10^{16} n/cm^2 for a $6\mu \times 9\mu \times 0.6\mu$ memory cell (Messenger et al, 1988, pp 1461-1463).

b. Nuclear Blast Radiation

Semiconductor devices designed to withstand the radiation from a nuclear detonation are manufactured with special radiation tolerant materials and are heavily shielded inside the spacecraft. In an exo-atmospheric nuclear explosion, ~80% of the energy results in soft X-rays, ~0.3% in gamma rays which cause the Electro-Magnetic Pulse (EMP), ~1% in neutrons, and the remaining ~19% in the debris kinetic energy.

Shielding would offer some degree of x-radiation protection for a satellite memory and other electronics. However, if a nuclear explosion was close enough, it is possible that x-rays could release enough electrons to disrupt the electric fields in an operating FEM device. This would obviously cause SEU. It has been estimated that an instantaneous pulse of 250,000 rads of x-radiation would cause SEU in a $6\mu \times 9\mu$ capacitor. (Messenger, 1988, p. 1463). Additionally, the EMP from a nuclear detonation would cause a current surge that could overload all spacecraft circuits and cause permanent damage. (Heins, 1992, personal conversation).

4. High density semiconductor

a. No Moving Parts

FERRAM's are semiconductors. There are no moving parts to wear out or jam. This could allow a longer period of service.

b. High density

Another attribute of semiconductor memories is that they are high density. Currently, Ramtron Corp. is producing 64 Kbit FRAM chips and is designing a 256 Kbit chip. Symetrix calculated that their ferroelectric material's dielectric constant should allow a minimum memory cell size of 2μ x 2μ which would enable very high density FERRAMs.

5. Low Power

It is well known that semiconductor memories use substantially less power than other types of memory. Table II shows some of Ramtron's FRAM power requirements.

Table II. RAMTRON FRAM POWER REQUIREMENTS

Component	Static Power	Read Power	Reference
FMx 1208	55 μW	44 mW	FMx 1208 data sheet
FMx 1408	55 μW	83 mW	FMx 1408 data sheet
FMx 1608	55 μW	220 mW	FMx 1608 data sheet

6. High Speed

FERRAMS are comparable to EEPROMs in operating speeds. Table III shows Ramtron's FRAM operating times.

Table III. RAMTRON FRAM OPERATING TIMES

Component	Read Access Time	Read Cycle Time	Write Cycle Time	Reference
FMx 1208	250 ns	500 ns	500 ns	FMx 1208 data sheet
FMx 1408	150 ns	300 ns	300 ns	FMx 1408 data sheet
FMx 1608	150 ns	300 ns	300 ns	FMx 1608 data sheet

7. Compatibility

FEM is compatible with both silicon and gallium arsenide (GaAs) manufacturing technologies. GaAs devices have superior speed and radiation hardness. Even the three volt operating level of GaAs circuitry does not appear to be a problem for FEM. (Scott (2), 1989, p. 1404)

C. UNDESIRABLE FEM CHARACTERISTICS

1. Fatigue

Recent FEM research has been focusing on fatigue--an undesirable characteristic that occurs from repeated toggling between polarization states. Fatigue is thought to be caused by oxygen vacancies that form in the ferroelectric layer. (Wight, 1990, p.1) It causes the hysteresis curve to flatten and the remnant polarization (+/-P_r) values to decrease in magnitude. As this happens, it becomes more difficult to distinguish between polarization states. Eventually (>10^9-10^{12} cycles), most FEM materials will not hold data. Symetrix claims that their ferroelectric material (Y1) does not fatigue. In a comparison of write cycle limits, EEPROMs tend to fail after ~10^5 cycles. Table VI shows some fatigue tests and results.

Table IV. FERROELECTRIC DEVICE FATIGUE TEST RESULTS

Manufacturer	Test # of cycles	P_r % of original	Reference
National Semi	5×10^{11}	~ initial value	Schwank et al, 1990, p.1604
Krysalis	10^9	50%	
Sandia	10^9	50%	
Krysalis	>10^{15}	unknown--still function	Wrobel, 1987, p.1
Ramtron FRAM	10^8	0 % loss	Ramtron
Ramtron test capacitor	10^{10}	75% loss	
Symetrix Y1	2.8×10^{11}	**100 %**	Moore et al_2, 1992, pp 9-10

Symetrix made major breakthroughs in ferroelectric material fatigue in mid-1991. They have developed a family of materials designated as "Y1" that show **no signs of fatigue** up to 2.8×10^{11} cycles. They are currently pursuing both national and international patents and licensing agreements and have not yet disclosed the material's composition.

2. Destructive Read Out (DRO).

As previously discussed, writing a bit of binary data is a simple procedure of applying +/- 5 volts to the capacitors of a FERRAM memory cell. Reading the data is a little more complex. A predetermined read voltage (for example +5 volts) is applied to the memory cell. If the cell has a "one" stored in it, the atom's position and corresponding polarity do not change. A current pulse that corresponds to the cell's charging current is generated. The read circuitry senses this current pulse. If the cell has a "zero" stored in it, the atoms will toggle to the "one" position and a current pulse of the cell's charging current **plus a switching current** is generated. The read circuitry can distinguish between the two states based on the total current. (Gnadinger, 1989, p.1-20) The problem is that in reading the zero, the data bit has been erased and must be rewritten. This procedure is called destructive readout. This characteristic is currently preventing FEM from serious contention for applications such as SDI (Alexander, 1992, phone conversation). Rapid read / restore and Error Detection And Correction (EDAC) software or differential partial cell sensing against a reference cell could virtually eliminate any problem with DRO (Messenger, 1988, p.1461). The space shuttle computers use EDAC in all of their computer memories.

D. COSTS

Currently only Ramtron is producing commercially available FRAMs. Their 64 KByte / two transistor / two capacitor (2T-2C) FRAM with memory cell sizes $\sim 150\ \mu^2$ sells for ~$1.00 per KByte. These prices are similar to standard EEPROM prices. The price is expected to drop to ~$0.50 per KByte in high volume production. Future FRAMs are being designed with a (1T-1C) memory cell. On 01 Dec 92 Ramtron announced that it will be working with Hitachi to co-develop a 4 Mbit Ferroelectric DRAM. (Bondurant, 04 Dec 92 phone conversation). It is reasonable to assume that costs will drop as more products are developed.

II. CURRENT MEMORY FORMS

A. OVERVIEW IN GENERAL

This chapter describes types of computer memory that are used by the military and / or are commercially available. The memory types will be broken down into three categories:

- Magnetic memories
- Semiconductor memories
- Optical memories

B. MAGNETIC MEMORIES

1. Magnetic Core Memory

Core memory is composed of rows and columns of hair-thin wires that intersect on small, (.013 in.) ferrite polarizing rings (Beyl, 1985, p. 1). The appropriate row and column wires are activated to write a single bit of data. A third wire is used to read the bit. (Beyl, 1985, p.1/Talley, 1992, p.10)

Core memory is still used in applications where there is a possibility of radiation degradation such as E-2 Hawkeye and EA-6B Prowler Navy aircraft. It is highly tolerant to radar and radiation sources and is still used in some Navy platforms. The Navy E2-C Hawkeye early warning aircraft has a 128 KByte memory unit that contains core memory. (Stiles, p.1) Table V shows core memory specific information.

Table V. CORE MEMORY INFORMATION

PRODUCT	CTS Fabri-tek MMS /32 (32 K x 18 bit words)
ACTIVE / STANDBY POWER	80 W / 28W
ACCESS / READ / WRITE CYCLE SPEED	350 ns / 900 ns / 900 ns
DENSITY(memory capacity)	72 Kbyte
ENDURANCE	unlimited
WEIGHT	3.5 - 3.9 lbs
SIZE (dimensions)	9" x 6" x 1.4 "
RADIATION TOLERANCE	no unclassified data available
COST	$5000
OTHER	Standard military memory system from 1960 - 1991
REFERENCE	Starnes, 1992, p.1 / Beyl, 1985, pp 1 - 6 / Morford, 1992, p.10

2. Magnetic Tape

Magnetic tape ranges in type from 1/4" cassettes to 12" reels of one inch wide tape still used in some Navy applications. Many spacecraft use magnetic tape where gigabytes of memory are needed to store data required for applications such as weather pictures.

For several military applications, mission operating software and databases are loaded onto computers using tape cartridges. Magnetic tape is still a very economical means of storing data. Table VI shows information on Techmar DAT tape storage system.

Table VI. MAGNETIC TAPE STORAGE INFORMATION

PRODUCT	Techmar DATavault 4000
ACTIVE / STANDBY POWER	23 W average
SUSTAINED DATA TRANSFER RATE	183 Kbytes per second
DENSITY(memory capacity)	4 Gbyte per 90 meter DAT tape
MEAN TIME BETWEEN FAILURE (MTBF)	> 50,000 hours
SIZE (dimensions)	4" w x 14.75"l x 7.11" h
WEIGHT	~ 8 lbs
COST	Drive: $5995, Tapes ~ $89 per tape
REFERENCE	TECHMAR DATavault literature

3. Magnetic floppy disk

Magnetic floppy disk is the most common type of personal computer secondary memory. The current sizes are 3 1/2" (1.44 MByte) and 5 1/4" (1.2 MByte). They are very economical and their memory capacity is appropriate for personal applications but limited for many military applications. Table VII shows information on a Procom floppy disk drive.

Table VII. MAGNETIC FLOPPY DISK SPECIFICATIONS

PRODUCT	Procom PXF1440/II floppy disk and drive
ACTIVE / STANDBY POWER	4.4 W / 1.8 W
ACCESS TIME	94 ns
SUSTAINED DATA TRANSFER RATE	250 Kbyte / sec
DENSITY(memory capacity)	1.44 Mbyte / 3.5" disk
MEAN TIME BETWEEN FAILURE (MTBF)	12000 hours
SIZE (dimensions)	External drive: 2" x 6" x 12"
WEIGHT	7 lbs
COST	$369
REFERENCE	Procom, 1992, p.24

4. Magnetic hard disk

Magnetic Hard disks have much higher memory capacities than floppy disks. The magnetic hard disk is usually permanently installed inside of the hard disk drive although some hard disk cartridges are removable from the drive unit. Figure 8 shows a hard disk drive removed from its case. Hard disks are designed to spin constantly which results in constant power consumption.

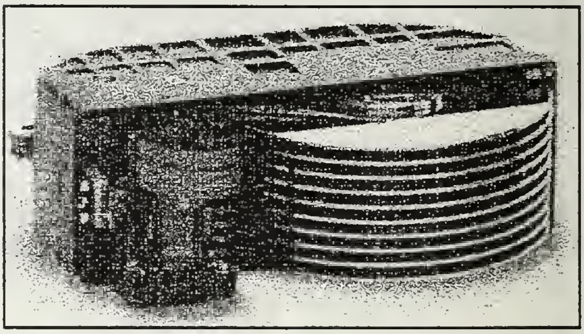


Figure 8. Hewlett Packard Hard Disk Drive

For aviation applications, a hard disk drive can be used only after the aircraft is in a stable flight profile, and must be heavily isolated from vibration. Hard disks may not be reliable and in fact may sustain permanent damage and data loss from the read/write head impacting the disk surface during non-normal flight situations. Computers containing hard drives can take minutes to reload if they encounter a software flaw or power is interrupted.

For spacecraft applications, a fast spinning hard disk and disk access maneuvers would create torques that would have to be countered in order to keep the spacecraft stable. Table VIII shows Hewlett Packard hard disk information.

Table VIII. HARD DISK INFORMATION

PRODUCT	Hewlett Packard HP 7957-59 Hard Disk
ACTIVE / STANDBY POWER	92 W average
ACCESS / READ / WRITE CYCLE TIME	17 ms / 1.4 ms per kbyte /
SUSTAINED DATA TRANSFER RATE	700 kbps
DENSITY(memory capacity)	81 GBytes
MEAN TIME BETWEEN FAILURE (MTBF)	73,000 hours
SIZE (dimensions)	12.8" x 11.2" x 5.1"
WEIGHT	23.2 lbs
COST	unavailable
REFERENCE	Hewlett Packard, 1992, pp 1-4

C. SEMICONDUCTOR MEMORIES

1. Programmable Read Only Memory (PROM)

PROM is a non-volatile semiconductor memory. Programming a PROM chip is performed by electrically "blowing" fuse links that permanently write the data into the chip's memory (Dressendorfer, 1991, p I-3). To alter programming, the entire chip must be replaced. Table IX shows Fujitsu PROM information.

Table IX. PROM INFORMATION

PRODUCT	Fujitsu MB7144H
ACTIVE / STANDBY POWER	130 mA / unavailable
ACCESS / READ / WRITE CYCLE TIME	55 ns / 24 ns / 60 ns
DENSITY(memory capacity)	8.192 Kbits
ENDURANCE	write once
SIZE (dimensions)	1.26 " x 0.52" x 0.2"
REFERENCE	Fujitsu MB7144E/H data sheet, 1984, pp 201-215

2. Erasable Programmable Read-Only Memory (EPROM)

EPROM chips can be erased and reprogrammed, but must be removed from their circuit board and exposed to ultraviolet light for approximately 20 minutes (Lahti, 1990, p.311). They can then be reinstalled and reprogrammed. Table X shows Cypress Semiconductor EPROM information.

Table X. EPROM INFORMATION

PRODUCT	Cypress Semiconductor CY7C285 EPROM
ACTIVE / STANDBY POWER	180 mA commercial / 200 mA military 40 mA commercial / 50 mA military
ACCESS / READ / WRITE CYCLE TIME	read: 20 ns comm / 25 ns mil
DENSITY(memory capacity)	512 kbit
ENDURANCE	100 cycles
SIZE (dimensions)	0.42" x 0.15" x 0.015"
RADIATION TOLERANCE	dose rate: 7 x 10^7 rad(si)/s total dose: 20 krad(si)
COST	comm: $40 / 100 units mil: $240 / 100 units
REFERENCE	Legenhausen, 1992, p.2

3. Electrically Erasable Programmable Read-Only Memory (EEPROM)

EEPROM chips can be programmed, erased and reprogrammed electrically without physical removal from their circuit board. Since they can be reprogrammed while permanently mounted and are non-volatile, they are versatile. Table XI shows Fujitsu EEPROM information.

Table XI. EEPROM INFORMATION

PRODUCT	Fujitsu MBM 28C64-25 EEPROM
ACTIVE / STANDBY POWER	110 mW / 550 mW
ACCESS / READ / WRITE CYCLE TIME	250 ns / 120 ns / 10 ms
DENSITY(memory capacity)	8.192 KByte
ENDURANCE	> 10,000 cycles
SIZE (dimensions)	1.45" x 0.58" x 0.23"
REFERENCE	Fujitsu MBM 28C64-25 data sheet, 1991, pp 1-8

4. Dynamic Random Access Memory (DRAM)

DRAM chips are a volatile memory. Each storage cell must be refreshed every few milliseconds in order to maintain the data (Mano, p.293). DRAM based circuit boards with a battery backup can be used as a pseudo non-volatile memory and can retain data for five years with a two Amp-Hour (AH) battery (Bloom, 1989, p.6). Table XII shows Fujitsu DRAM information.

Table XII. DRAM INFORMATION

PRODUCT	Fujitsu MB814100A DRAM
ACTIVE / STANDBY POWER	155 mA / 135 mA
ACCESS / READ / WRITE CYCLE TIME	70 ns / 125 ns / 175 ns
DENSITY(memory capacity)	128 kbyte
ENDURANCE	unlimited
SIZE (dimensions)	1.45" x 0.58" x 0.23"
REFERENCE	Fujitsu MB814100A DRAM data sheets, 1992, p.1-7

5. Static Random Access Memory (SRAM)

SRAM chips are also a volatile form of memory. Unlike DRAMs, they do not need periodic refreshing. SRAMs can also be made pseudo non-volatile with a battery backup. An example of memory retention is four years with a 35 milli-Amp-Hour (mAH) battery (Bloom, 1989, p 6). Table XIII shows information on a Cypress Semiconductor SRAM.

Table XIII. SRAM INFORMATION

PRODUCT	Cypress Semiconductor CY7C109 SRAM
ACTIVE / STANDBY POWER	140 mA / 35 mA
ACCESS / READ / WRITE CYCLE TIME	25/ 25 ns / 25 ns
DENSITY(memory capacity)	1 Mbit
ENDURANCE	cycles
SIZE (dimensions)	0.6" x 0.25" x 0.015"
RADIATION TOLERANCE	20.9 krads min / 24.1 krads average
COST PER Mbit	$ 56 (large quantity commercial) $110 (large quantity military)
REFERENCE	Legenhausen, 1992, p.1

6. Flash EEPROM Memory

Flash memory is a recent innovation. Intel has developed a flash memory card that is the same size as a credit card (except four times as thick) that holds 20 Mbytes of non-volatile RAM. Flash EEPROMs are faster and have higher endurance than standard EEPROMs. Tables XIV and XV show information on Intel flash EEPROM memory cards and Targa flash EEPROM cartridges.

Table XIV. INTEL FLASH MEMORY INFORMATION

PRODUCT	Intel flash memory card
ACTIVE / STANDBY POWER	25 mA / 400 μA
ACCESS / READ / WRITE CYCLE TIME	200 ns / ~200 ns / 10 μs (per byte)
SUSTAINED DATA TRANSFER RATE	16.6 MBytes / sec
DENSITY(memory capacity)	1, 4, 10 and 20 Mbyte
ENDURANCE	100,000 cycles
MEAN TIME BETWEEN FAILURE (MTBF)	1,000,000 hours
SIZE (dimensions)	85 mm x 54 mm x 3.3 mm
WEIGHT	0.93 oz
COST	1 Mbyte: $165 / 2 MByte: $236 / 4 MByte: $310 10 MByte: $519 / 20 MByte: $ 958
REFERENCE	Snyder, 1992, pp 1 - 11

Table XV. TARGA FLASH MEMORY INFORMATION

PRODUCT	Targa 100 Mbyte flash memory cartridge
ACTIVE / STANDBY POWER	1 W / 100 mA
ACCESS / READ / WRITE CYCLE TIME	1.5 ms / unreported / unreported
SUSTAINED DATA TRANSFER RATE	650 KBytes / sec
DENSITY(memory capacity)	100 Mbyte
ENDURANCE	100,000 cycles
MEAN TIME BETWEEN FAILURE (MTBF)	70,000 + hours
SIZE (dimensions)	7" x 5.75" x 1.5"
WEIGHT	1.5 lbs
COST PER Mbit	$ 15,970 (cartridge) + $625 (interface)
REFERENCE	Fronsee, 1992, pp 1-4

D. OPTICAL MEMORIES

1. Optical Read / Write Disk

Optical disk memory uses a laser to write data to and read data from the metal layer of a plastic-metal-plastic layered disk. Optical disks are designed to spin continuously and therefore draw continuous power. Optical disk memory systems are very high capacity and very fast. Since only the laser beam is in contact with the disk, optical disk memory systems are not in danger of damage/data loss from head/disk impact as are magnetic hard disks. Table XVI shows information on a Plasmon optical disk drive.

Table XVI. PLASMON OPTICAL DISK INFORMATION

PRODUCT	Plasmon RF-7010 Drive & 1 Gbyte disk cartridge
ACTIVE / STANDBY POWER	30 W average
ACCESS TIME	90 ms seek
SUSTAINED DATA TRANSFER RATE	4 Mbyte / sec
DENSITY(memory capacity)	1 Gbyte / 5.25" disk
MEAN TIME BETWEEN FAILURE (MTBF)	20,000 hours
SIZE (dimensions)	9.5" x 11" x 5"
WEIGHT	16.4 lbs
COST	Drive: $3995, Disks:$250 each
REFERENCE	Plasmon RF-7010 and disk literature

2. CD Read Only Memory (CD ROM)

CD ROM memory systems use a laser to read previously recorded data from an optical disk similar to an audio compact disk. A CD ROM disk can hold 650 Mbytes of information. This memory system may also prove very rugged and would probably work well for some military applications such as operating programs or computer charts and maps. Table XVII shows information on a Procom CD ROM drive.

Table XVII. PROCOM CD ROM INFORMATION

PRODUCT	PICDL(internal) / PXCDL(external)
ACTIVE / STANDBY POWER	7 W average
ACCESS TIME	380 ms (ave) / 800 ms (max)
SUSTAINED DATA TRANSFER RATE	150 kByte / s
DENSITY(memory capacity)	650 Mbyte / CD
ENDURANCE	unlimited
MEAN TIME BETWEEN FAILURE (MTBF)	15,000
SIZE (dimensions)	External: 1.9" x 5.9" x 12" Internal: 1.69" x 5.75" x 8"
WEIGHT	External: 5.75 lbs Internal: 3.31 lbs
COST	External: $395 Internal: $325
REFERENCE	Procom PCDL data sheets, 1992, p.2

3. Holographic Memory

Holographic memory is moving out of the research stage into product development. Data is stored as two dimensional patterns of light in optical recording media such as a photo refractive crystal. A typical storage medium is a 5 mm thick, 5 cm by 5 cm square array of strontium barium niobate fibers. Figure 9 shows how the data fields are arranged as stacks of pages in the crystal. The data is written by splitting a laser beam into a reference beam (that locates the proper address page) and a data beam. When the

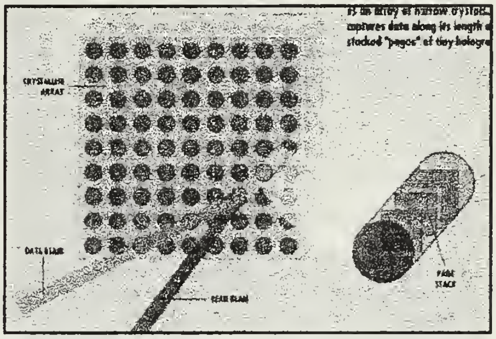

captures data along its length
stacked "pages" of tiny hologr
CRYSTALLINE ARRAY
DATA BEAM
PAGE STACK

Figure 9. Holocube Memory Storage

two beams cross, they interfere with each other causing an interference hologram which is recorded in the photo-reactive crystal.

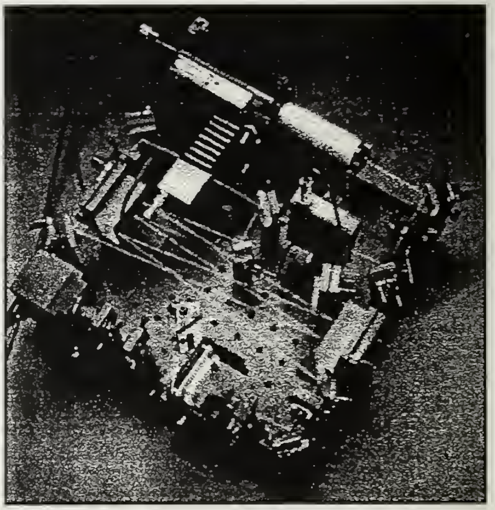


Figure 10. Experimental Holographic Memory Device

Reading the data is achieved by a reference beam illuminating the proper page that corresponds to the desired information. The reflected light is a reconstruction of the original data pattern which is converted to a digital signal on a detector array. Figure 10 shows a holographic memory setup. Holographic memory promises gigabytes of data storage in a single crystal. (Tamarack, 1992, pp. 1-4). Table XVIII shows information on an experimental holographic memory unit.

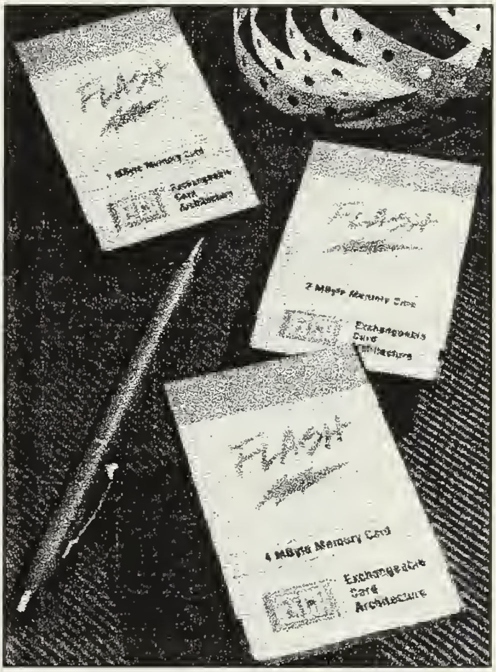
Table XVIII. HOLOGRAPHIC MEMORY INFORMATION

PRODUCT	Tamarack Storage Devices prototype
ACTIVE / STANDBY POWER	40 W / 1 W
ACCESS / READ / WRITE CYCLE TIME	5 ms / 30 ms / 30 ms
SUSTAINED DATA TRANSFER RATE	3 MBPS
DENSITY(memory capacity)	50 GBytes / sec
MEAT TIME BETWEEN FAILURE (MTBF)	50,000
WEIGHT	proprietary
SIZE (dimensions)	proprietary
COST	read / write unit: \$3500 - \$5000 write once memory block: ~\$0.01 / MByte write many memory block: ~\$1.00 / MByte
REFERENCE	Johnson, 1992, pp 1-4

III. FEM CHARACTERISTICS RELATED TO THE MILITARY

A. PROPOSED FEM PACKAGING FOR MILITARY PURPOSES

There are two physical forms for FEM that would be useful in military applications. First, an internal FERRAM board could replace primary computer memory RAM boards. Ramtron developed an 8 KByte FRAM evaluation and development system (FEDS) board that became available in January 1991. It was based on their lowest capacity 4 Kbit FMx 1208 chip, (Bondurant, 1991, P.308/309). As FERRAM technology develops, memory capacities will increase dramatically. Second, a portable memory card or cartridge could replace secondary memory such as magnetic disks and tape cartridges, and a "solid state drive" could be developed and used for large memory capacity applications. Examples of these packaging methods are as follows. Figure 11 shows's Intel 1, 2, and 4 Mbyte memory cards. They have just released a 20 MByte card that is the same size. Figure 12 shows a



Flash
1 MByte Memory Card
Exchangeable Card Architecture
Flash
2 MByte Memory Card
Exchangeable Card Architecture
Flash
4 MByte Memory Card
Exchangeable Card Architecture

Figure 11. Intel Flash Memory Cards

100 MByte flash memory cartridge and Figure 13 shows a permanent mount 80 MByte flash "solid state" drive (Targa, 1992, technical data sheets).

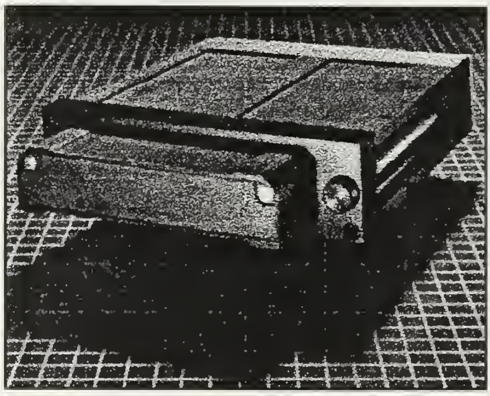


Figure 12. 100 MByte Flash Memory Cartridge

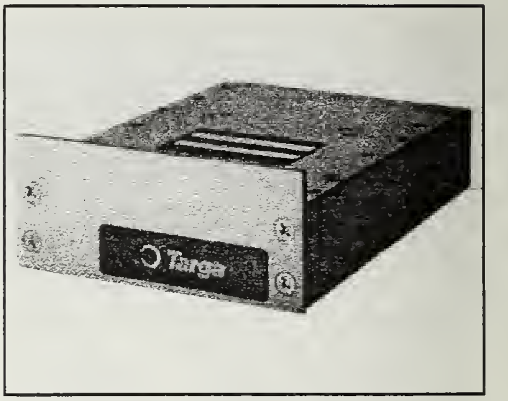


Figure 13. Targa 80 Mbyte Flash Memory Unit

B. ADVANTAGES OF FEM FOR MILITARY APPLICATIONS

1. Non-volatility

a. Primary Computer Memory

Internal semiconductor computer memory is referred to as primary memory. Two examples of primary memory are personal computer internal RAM and cache memory. DRAMs or SRAMs are used for internal RAM chips because they are inexpensive, dense and have very high endurance. They perform well under normal circumstances. A problem arises when there is a power fluctuation or failure--***volatile memory loses data.*** A computer with volatile RAM must be re-initialized and the operating program reloaded. A computer operating memory composed of FERRAM chips ***would not lose data!*** Instead of re-initializing the computer and then reloading the operating program and user data, the computer could be turned back on and it would 'wake up' in the program and user file exactly where it was prior to the problem event. The greatest loss would be at most a few seconds of incoming data that would not be recorded while the computer was reset.

(1) Primary memory in Naval aviation. The possibility of zero data loss would be extremely valuable to Naval aviation. Most aircraft missions are required to abort if the internal computer memory is lost during flight. The aircraft computer may have the capability to be reloaded during flight but the resulting mission data is usually less effective than with software loaded before flight due to imprecise navigation data. In the carrier aviation environment, any avionics emergency requires the crew to abort the mission and return to the carrier. The risk of life and aircraft loss is too great to attempt lengthy in-flight computer reload and resume the mission. FEM would allow near instantaneous program 'wake up' and mission continuation if the problem was an isolated power spike or software glitch.

(2) Primary memory in military spacecraft. The benefits of non-volatile FEM would apply to military spacecraft as well. Current primary memory usually consists of EEPROMs or core memory which are larger, slower, and consume more power than FEM.

b. Secondary Computer Memory

Secondary memory is used to store operating programs, databases and user / mission data until needed by the central processing unit. This type of memory is non-volatile and sometimes portable. Magnetic tapes and disks are examples of secondary memory.

For most military aircraft, current mission databases and programs are loaded into aircraft computers from magnetic tape or disks. Post-flight mission data is also removed from the aircraft for analysis using tapes or disks. Removing the mission data from the aircraft allows the aircraft to be in an unclassified status so that maintenance personnel without security clearances can work on the aircraft..

An additional benefit of an aircraft computer memory consisting solely of FEM is that an alert status aircraft could be pre-flight inspected, pre-loaded with all mission data and put on alert status. It could be launched from engines and power off status in merely the time it takes to load the aircraft's crew, start the engines and complete the safety checklists. Therefore, an alert aircraft could be launched much faster than current procedures allow and would not require external power and air conditioning to maintain data loaded before the flight.

2. Semiconductor

a. No Moving Parts

One of the most significant features of a semiconductor memory is the fact that there are no moving parts. Most people are familiar with cassette tapes and floppy disks which have moving parts. Tapes tend to stretch which can distort analog data and are also prone to become sticky over time. Floppy disks are a great improvement over tapes, but are subject to damage / data distortion from dust and dirt particles.

The second disadvantage of memory systems with moving parts is that they eventually wear out and fail. This is usually not a major factor for commercial ground based applications. However, it is of great concern for aviation and space applications. Military aircraft are subject to heavy vibrational and gravitational forces that can cause moving parts to jam or fail suddenly and prematurely. The minimum resulting damage is mission termination. Replacement costs are usually high and the aircraft is unavailable for missions until the problem is fixed. For space applications, a faulty or failed data recorder severely limits or incapacitates the spacecraft mission.

The third disadvantage of memory types requiring moving parts is that they need a drive unit which can be very heavy and bulky as in the case of 12 inch magnetic tape recorders. A smaller example of a drive unit is a hard drive used in laptop computers.

Small semiconductor memory units however, can be mounted either permanently on one of the internal computer boards or temporarily as in a removable data card or cartridge that plugs directly into the computer circuitry. Semiconductor cards and cartridges may require an interface box slightly larger than the cartridge to be mounted inside the computer.

For space applications, a solid state memory eliminates the problem of torques from spinning motors and moving parts. Since there are no torques, no counter-torquing devices are required. Therefore the spacecraft memory unit can be made smaller, lighter and less complex.

b. High Density

Following are two examples of semiconductor products demonstrating very high memory capacities. The first example is Irvine Sensor Corporation's stacked SRAM chips. Figure 14 shows a stack of four SRAM chips assembled into a thin package with the same footprint as a single SRAM. The

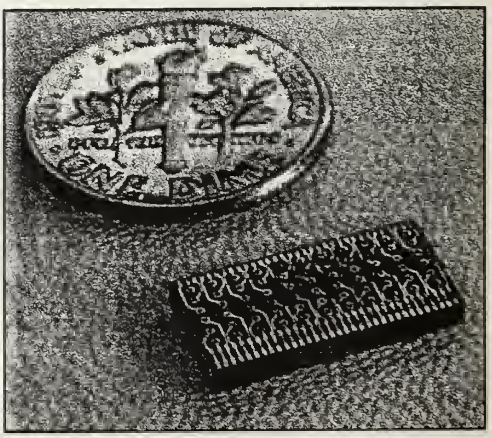


Figure 14. Irvine Sensor's Short Stack SRAM

resulting 4 Mbit / 512 KByte chip is smaller than a dime. (Military & Aerospace Electronics, 1992, p.37)

Figure 15 shows the second example of dense solid state memory: a PC memory card. It is a thin, flat memory card that can be inserted into an internal or external reader slot. (Lee, 1992, p.30)

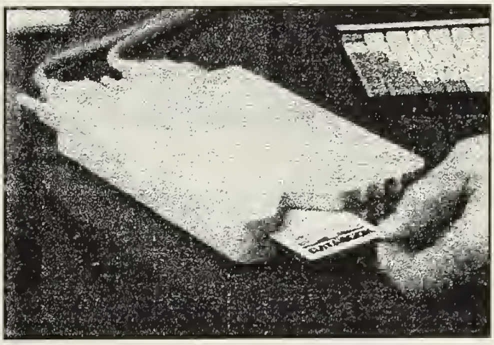


Figure 15. Databook External Card Reader and Memory Card

c. *Sealed Packaging*

Since FEM is a semiconductor memory, it is not sensitive to dirt and dust like memory with moving parts. However FEM chips are sensitive to water and humidity. As with any circuitry, water can short-circuit the devices and humidity can corrode electrical contacts. FEM primary memory boards can be sealed inside a computer away from contaminants. FEM secondary memory cards and cartridges can be sealed so that only contacts on one end are exposed. Such packaging would allow them to be carried in a pocket and be usable in any environment except direct water immersion.

d. *Random Access*

Magnetic tape memory is arranged serially so that when data is needed from the middle of the tape, the computer must first read through everything before it. Serial access is very time consuming. FERRAM data is arranged in a manner that allows the computer to review the contents in memory when it is turned on and then access and read only the data needed in a matter of nanoseconds.

3. Inherent Radiation Hardness

The aviation environment is very hostile. There are two sources of radiation to be concerned about: first is the aircraft's own radar. Every aircraft has a weather radar and possibly a mission specific radar. The aircraft's computer memory must be radiation hard to avoid data loss and damage which could result in aborting the mission and possibly aircraft loss. Current aircraft memory is made of either core or heavily shielded semiconductor memory.

The second source of radiation is from solar/cosmic rays. Most aircraft operate at altitudes between 1000-40000 feet. Radiation is much stronger at higher altitudes because it is filtered through less atmosphere. Data has been collected from E-3 / AWACS aircraft (29,000 feet cruise altitude) and NASA ER-2 aircraft (65,000 feet cruise altitude) and various military flights. Analysis has shown that incidents of SEU increased with altitude and also with increased latitude. (Raynor, 1992, p.1)

As shown in Chapter 1, FEM is radiation hard and therefore would substantially reduce SEU related problems. A simple way of looking at standard FEM is that it will withstand much more radiation than a human could and would be applicable to all manned missions and spacecraft that are not designed to withstand nuclear detonation radiation.

4. Stability in Magnetic Environment

In military aviation, there have been isolated instances of small data changes or losses or where the cause was thought to be magnetic fields. For instance, in a stored text file several pages long, one or two paragraphs would be garbled or have parts missing upon retrieval. A second example was a template database program that suddenly became confused and repeatedly malfunctioned for no apparent reason. In both cases, the file and program was removed from the disk, the disk was checked for errors and none were found. The disk was then reloaded with new files / programs. They functioned properly. FEM is not affected by magnetic fields and would therefore benefit both aviation and space applications.

5. Low Power

On a spacecraft, power budgets are extremely critical. Due to the cost and weight of producing power from solar arrays, it should be understood that the less power required, the smaller, lighter and less expensive the spacecraft can be made. Additionally, a lighter spacecraft is cheaper to launch. A simple cost analogy is that every pound of spacecraft costs a pound of gold to launch.

Military aircraft do not have strict power budgets. With one or more jet engines driving generators, electrical power is usually not a problem. Therefore, FEM's low power consumption is not a major factor for military aviation.

6. Speed

Military designs and requirements for spacecraft and aircraft computers are constantly being improved though they tend to lag behind the fastest and most capable commercial computers. As computer processing speeds increase, faster data access is required. FEM's 300 ns read and write cycle time is acceptable.

7. Reduced Weight

When FEM technology approaches DRAM density, it is foreseeable that current memory requirements could be met by FERRAM modules that are much smaller than existing memory modules. A gross example of this is in the Navy's E-2 Hawkeye early warning aircraft. Its main memory unit is composed of magnetic core memory, holds 128 Kbytes, occupies 6.2 cubic feet and weighs ***792 lbs!*** (The E-2 will be fully discussed in Chapter VI.) Ramtron is expecting to have 64 kbit chips in production by the end of this year. They are designing a 256 Kbit chip and have announced that they are working with Hitachi to co-develop a 4 Mbit Ferroelectric DRAM.

A very important aspect of aviation memory is *weight.* Every pound of equipment needed for the mission is a pound of fuel that is lost. For the E-2 Hawkeye, 600 pounds of fuel means 15 minutes of flight time. This translates to 15 minutes of extra mission time, or more importantly, 15 minutes of emergency action time if needed.

Figure 16 shows one of Intel Corporation's one, two and four MByte flash memory cards. As previously mentioned, they have recently released a 20 MByte memory card that is the same size. It is logical to assume that as FEM technology develops, FERRAMs can achieve similar densities. Current military space and aviation primary and secondary RAM memory requirements could be met by a single FERRAM memory card.

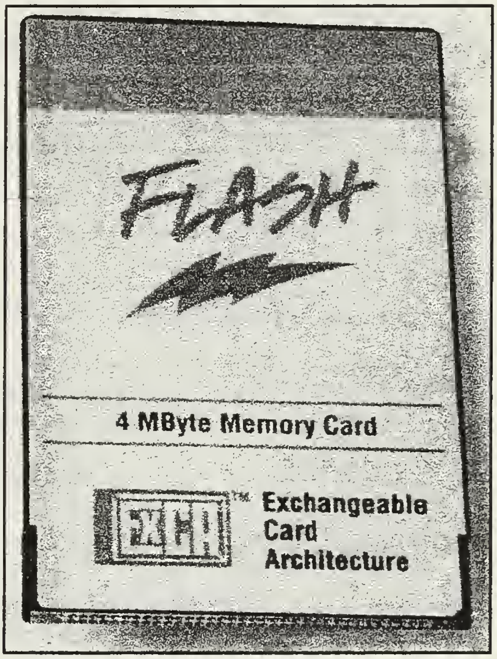


Figure 16. Intel Flash Memory Cards

IV. SPACECRAFT COMPUTER MEMORY

A. SPACECRAFT MEMORY TYPES

1. Solid State

Current operational spacecraft use various forms of solid state memory ranging from plated wire to semiconductors. The Hubble space telescope, Intelsat 6, Landsat and space shuttle computer memories will be discussed in this chapter. Their solid state memory types include plated wire, PROM, and SRAM.

2. Tape

Tape recorders are used for space applications requiring GBytes of information such as digital weather imagery. There are a wide variety of spacecraft tape recorders in service and under development. Table XIX shows volumetric information on a few spacecraft tape recorders (Featherstone, 1992, p.3 / GE Aerospace, 1992, p.1).

Table XIX. SPACECRAFT TAPE RECORDER INFORMATION

Recorder	Memory Capacity	Size	Weight	Power Read / Write	Program
Odetics DDS-5000	1.7 Gbit	9" x 14" x 7"	23 lbs	23 W / 41 W	DMSP NOAA Tiros
Odetics DDS-5000EC	6.6 Gbit	11" x 15" x 10"	43 lbs	30 W / 73 W	ERS-1, ERS-2
Odetics DDS-6000EC	77 Gbit	TU: 20" x 20" x 13" EU: 11" x 21" x 15"	160 lbs	110 W / 215 W	SPOT-1,2,3 Landsat 6 Radarsat
Odetics DDS-9000	250 Gbit	TU: 20" x 20" x 13" EU: 11" x 21" x 15"	160 lbs	238 W / 300 W	proposed for EOS Polar sat
Odetics DDS-5000 (lightweight)	25 Gbit	TU: 15" x 13" x 12" EU: 13" x 11" x 11"	65 lbs	60 W / 112 W	proposed for EOS Polar sat
GE STR-108 (AT) (2 TU)	1 Gbit	6" x 7.75" x 11"	20.6 lbs	10 W / 18 W	numerous
GE STR-20	10 Gbit	8" x 6.25" x 12"	80 lbs	14 W / 35 W	numerous
GE STR-50	25 Gbit	TU: 6.25" x 8" x 4" EU: 12.5" x 16" x 3.5"	28.1 lbs	18 W / 45 W	numerous

TU = Transport Unit EU = Electronics Unit

Figures 17 and 18 show the GE STR-108 recorder transport unit and fully packaged transport and electronics unit.

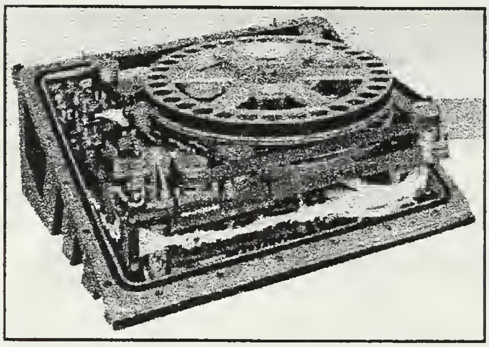


Figure 17. GE STR-108 Tape Recorder Transport Unit

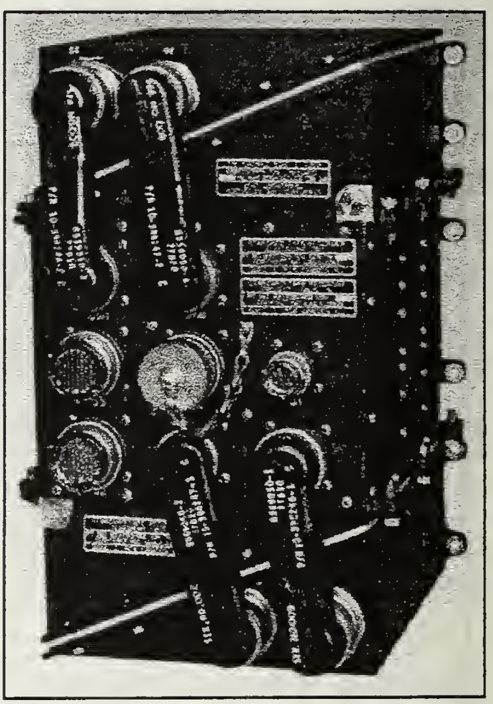


Figure 18. GE STR-108 Transport Unit and Electronics Unit

3. Twin Counter-Rotating Hard Disks

One technology has not yet been tested in space but deserves mention is Spectrum Astro's Erasable Disk Mass Memory (EDMM). Spectrum Astro is being sponsored by USAF Phillips Laboratory and DARPA Advanced Space Technology Program to determine the feasibility of using commercially available state-of-the-art hard disk drives for space applications. They currently have two 3.5 inch, shock mounted, back-to-back, hermetically sealed, space wiring compatible prototype memory units. Both use Conner Peripherals hard disk drives.

Table XXI shows specific EDMM data. (Cleveland. 1992, pp 9, 17)

Table XX. EDMM INFORMATION

Component	Memory Capacity	Size	Weight	Average Power
EDMM-1 CP 3540 hard disk	2 x 543.7 Mbytes = 1.08 Gbytes	10.2" x 8" x 5"	9.2 lbs	17 W
EDMM-2 CP Baja hard disk	2 x 1.37 Gbytes = 2.74 Gbytes	10.2" x 8" x 5"	10 lbs	18 W

The EDMM-1 is scheduled to be tested aboard the STEP-3 satellite in early 1995.

Figure 19 shows EDMM-1 with and without its cover.

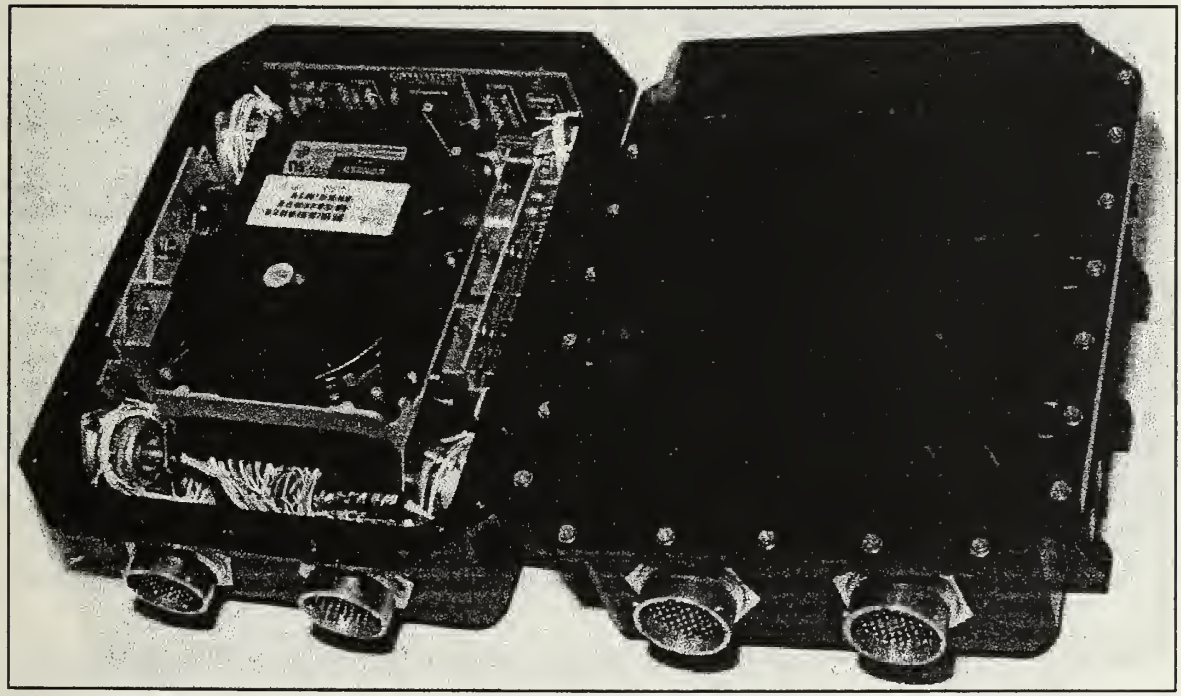


Figure 19. Spectrum Astro Erasable Disk Mass Memory unit

B. REAL WORLD EXAMPLES OF SPACECRAFT MEMORY

1. Space Shuttle

Figure 20. Space Shuttle Orbiter

Figure 20 shows a space shuttle orbiter. Each of the orbiters were originally equipped with five IBM AP101B core memory based General Purpose Computers (GPC). In December 1991 the last orbiter was upgraded to five IBM AP101S SRAM based GPCs. Table XXI shows the shuttle GPC memory information.

Table XXI. SPACE SHUTTLE MEMORY INFORMATION

Component	Memory Capacity	Size	Weight	Power
IBM AP101B GPC (Core memory)	104 Kbytes	7.6" x 20.4" x 19.5"	120 lbs each 600 lbs total	650 W (each)
IBM AP101S GPC (CMOS memory)	256 Kbytes	7.6" x 10.2" x 19.5"	64 lbs each 320 lbs total	560 W active (each) 56 W standby (each)
Mass Memory Units (2)	8.39 x 10^6 words (unknown # bits / word	11.6" x 15 " x 17.5"	24.5 lbs each 73.5 lbs total	77 W active (each) 20 W standby (each)

Since SRAMs are volatile, each GPC uses power even when in the standby mode (56 W each). Additionally, each GPC has a NiCad battery to maintain memory for analysis in case of a GPC failure.

Radiation protection is achieved by the use of an active EDAC routine that can correct single failures and detect but not correct multiple failures. The memory is designed so that each bit is on a separate chip in case of chip failure. (Dubrovin, 1992, p. 1) Two 8 x 10^6 word magnetic tape mass memory units store three copies of mission software each.

2. Landsat

Figure 21 shows the Landsat spacecraft. It is a commercial land remote sensing satellite. Landsat V was launched in 1984. It has three separate memories: the flight computer memory, the telemetry recorder, and the image data recorder. Table XXII shows specific memory information (Mertz, 1992, pp 1-15).

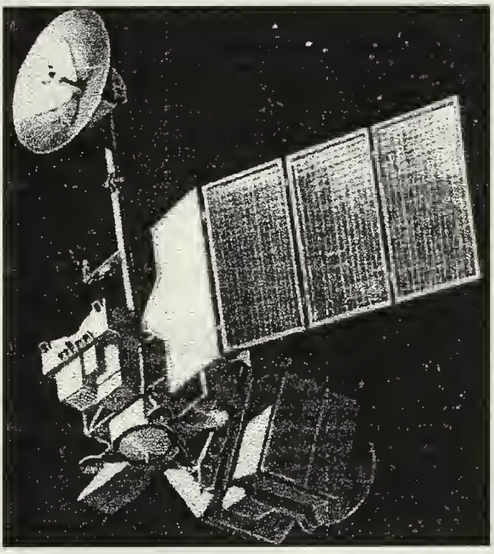


Figure 21. Landsat spacecraft

Table XXII. LANDSAT MEMORY INFORMATION

Component	Memory Capacity	Size	Weight	Power
Flight computer memory (SRAM)	64 K words: each word = 16 information bits + 6 EDAC bits	10.2" x 9.9" x 0.65"	1.3 lbs	145 W
Telemetry recorder (SRAM)	9 Mbits	11.5" x 19.9" x 14.2"	14.04 lbs	10 W standby 21 W active
Image data tape recorder	75 Gbits	Electronics unit: 20" x 12" x 15" Tape transport: 20" x 20" x 13"	Electronics unit: 54 lbs Tape transport: 106 lbs	Record: 177 W Play: 255 W Standby 48 W

3. Intelsat VI

Figure 22 shows the Hughes built Intelsat VI spacecraft. It is a very capable communications satellite that can handle 120,000 two-way phone calls and three television channels at once. It is a real time system that transmits signals as they are received. There is no store and forward capability and therefore no need of any mission data recorder or memory as seen in the weather satellites.

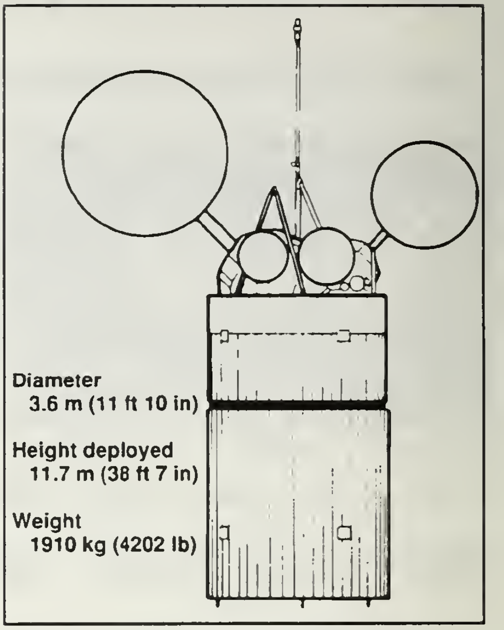


Figure 22. Intelsat VI Communication Satellite

Intelsat VI was designed for a specific purpose and has limited computer memory. Only 22 KBytes of RAM were designed into the satellite's altitude control computer (the only component containing RAM). The memory consists of 22 1-KByte SRAM chips. Figure 23 shows a two board section from the attitude control computer that consists of PROMS, SRAMS and other devices (Johnson, 1992, p.3 / Linberg, 1992, phone conversation / Shimogake, 1992, phone conversation).

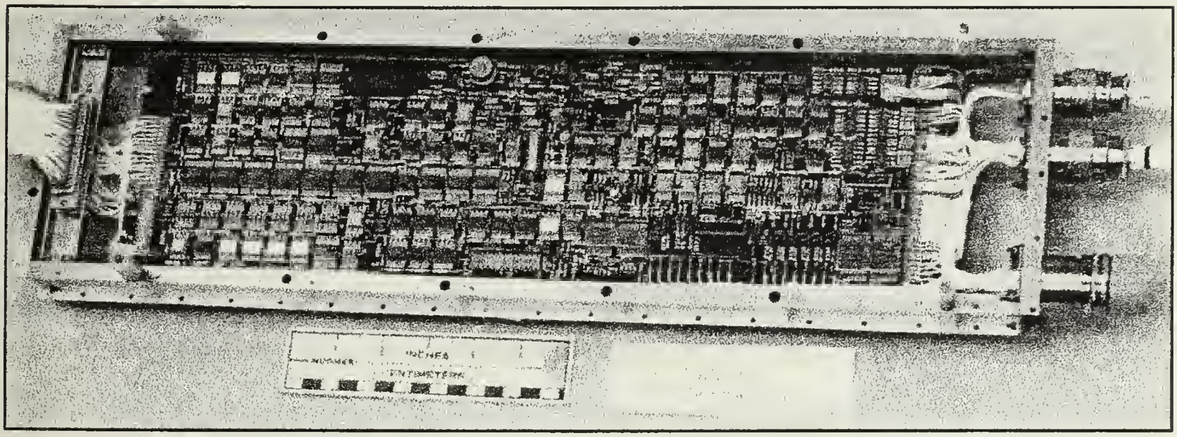


Figure 23. Intelsat VI Attitude Control Computer Board

4. Hubble Space Telescope

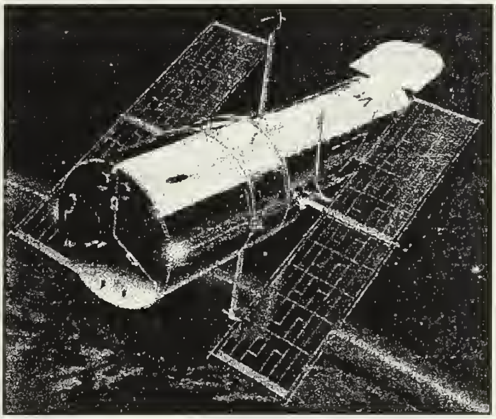


Figure 24. Hubble space telescope

Figure 24 shows the Hubble Space Telescope. The Hubble contains two forms of secondary memory. The DF-224 flight Computer's CPU primary memory uses P-channel MOS semiconductors, but the six memory units are made with plated wire technology. Hubble uses three mass memory tape recorders for mission data. Table XXIII shows specific memory information.

Table XXIII. HUBBLE MEMORY INFORMATION

Component	Memory Capacity	Size	Weight	Power
DF-224 flight computer	65 K x 25 bit words	18" x 18.8" x 13"	110 lbs	100 watts
6 plated wire memory units	8192 x 25 bit words	~ 9"x 12" x 1.5"	unknown	unknown
Odetics engineering / science tape recorders	~ 1.24 GBytes each	12.75" x 10" x 7 "	20.5 lbs each 61.5 lbs total	20 W record (each) 27 W play (each)

C. POSSIBLE FEM SPACE APPLICATIONS

Table XXIV reviews the memory requirements of the previous platforms.

Table XXIV. SPACECRAFT MEMORY SUMMARY

Platform	Memory Unit	Capacity
Space Shuttle	AP101S internal SRAM units (5)	256 KBytes
	Mass Memory Units (2)	~ 8.39 x 10^6 words / tape
Landsat	Flight computer Internal SRAM	160 KBytes
	SRAM Telemetry Recorder	1.125 MByte
	Image data tape recorders	75 Gbits
Intelsat VI	Attitude Control Unit Ram	22 KBytes
Hubble Space Telescope	Plated Wire Memory Units (6)	~25 KBytes each
	Mass Memory Recorder (3)	~ 1.24 Gbits each

Most of the spacecraft memory requirements are beyond the immediate capabilities of commercially available FRAM devices. Each of the shuttle's 256 KByte RAM requirements could be filled with 32 FMx 1608 8 KByte devices. Landsat's flight computer internal RAM (160 KByte total) requirement could be satisfied with 20 FMx 1608 FRAMS. Intelsat VI's 22 KByte of RAM requirement could be satisfied with three FMx 1608 FRAMs.

The mass memory storage devices can obviously store more data than FEM devices can at this time. However, as FEM technologies improve and memory capacities increase, it is possible that a solid state FEM mass memory unit could meet or exceed conventional tape mass memory unit capacities for the same weight and volume requirements.

V. TWO EXAMPLES OF NAVAL AIRCRAFT MEMORY

The basic mission computer components for two Navy carrier based aircraft will be discussed. Only basic sizes, weights and memory capacities will be presented.

A. E2-C HAWKEYE EARLY WARNING AIRCRAFT

Figure 25 is a picture of the Navy's only carrier based AEW aircraft.

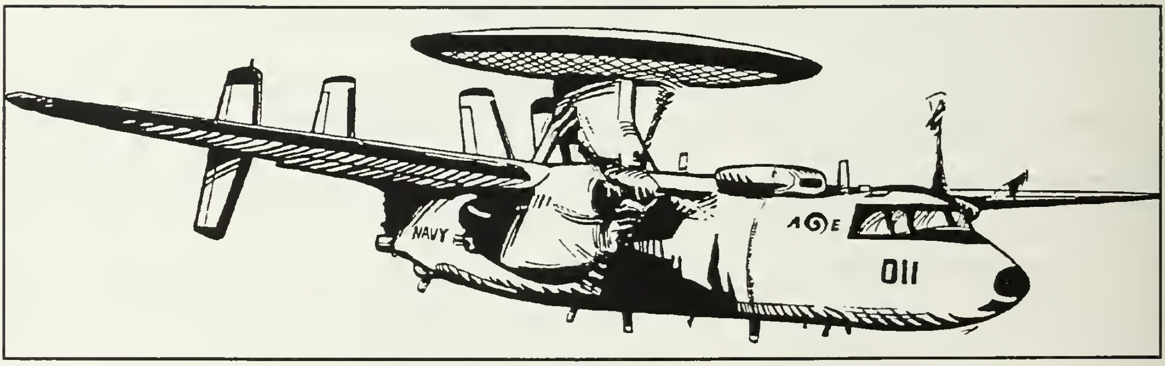


Figure 25. Navy E-2 Hawkeye AEW aircraft.

The E-2 is one of the oldest aircraft designs in the fleet. The prototype's maiden flight was in October of 1960. There have been three different versions with the latest being the Group 2 upgrade. (Tinsley, 1992, conversation). All three designs rely on the same core memory based computer. Table XXV shows specific component information.

Table XXV. E-2 HAWKEYE MISSION COMPUTER INFORMATION

Component	Memory Capacity	Size	Weight
Operating computer (DDBC)	32 KByte	14" x 8" x 5 "	21 lbs
L304 Main Memory	128 KByte	43" x 19" x 13"	792 lbs
High Speed Printer (HSP)	64 KByte	10" x 9.5" x 8"	37 lbs

B. EA-6B PROWLER ELECTRONIC COUNTER MEASURE AIRCRAFT

The EA-6B Prowler is the Navy's electronic countermeasures aircraft. It accompanies attack aircraft and jams the enemy's radar during bombing missions. Figure 26 shows an EA-6B.

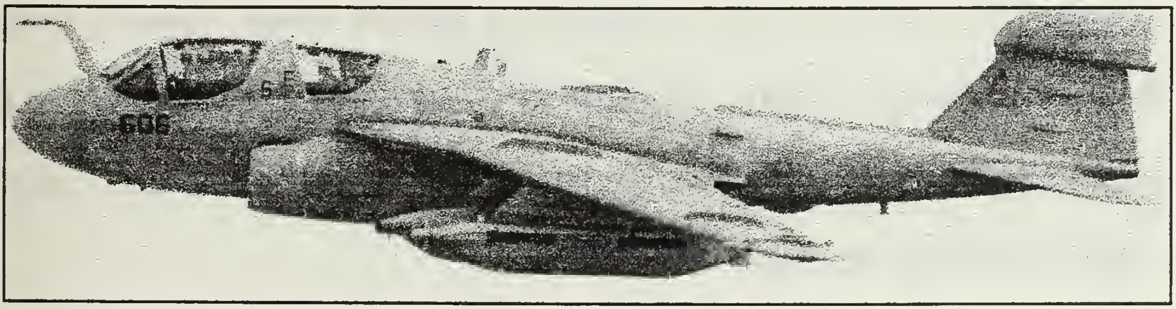


Figure 26. Navy EA-6B Prowler ECM aircraft.

Part of the EA-6B's mission computer contains core memory. Table XXVI describes the components and their sizes.

Table XXVI. EA-6B PROWLER COMPUTER INFORMATION

Component	Memory Capacity	Size	Weight
Display Computer	48 KByte	10.5" x 16.5" x 7.75"	44.5 lbs (total) (2 x 3 lb memory modules)
Central Mission Computer (CMC)	384 KByte (64 KByte SRAM 128 KByte EEPROM 2 x 32 KByte Core 2 x 64 KByte Core)	10.25" x 25" x 8.5 "	60.5 lbs (total) SRAM + EEPROM: 2.1 lb 32k Core: 2 x 3.1 lb 64k Core: 2 x 4.5 lb
Computer Interface Unit / Encoder	192 KByte (64 KByte SRAM 128 KByte EEPROM)	13.25" x 20.5" x 7.5"	60.5 lbs (total) memory board: 2.1 lb

The future advanced capability (AVCAP) Prowler's mission computer memory is designed with 100% semiconductor memory. It will be composed of roughly 75% SRAM and 25% EEPROM. A problem already apparent to the designers is that the AVCAP computer is estimated to take 15 minutes to load in preparation for a mission vice a shorter (classified) time for existing systems (Morford, 12 Nov 92, Phone Conversation).

C. POSSIBLE FEM APPLICATIONS IN NAVY AIRCRAFT

Since core memory comprises part of the E-2's and EA-6B's main memory, it is easy to see that almost any of the radiation hard semiconductor types could fulfill the need in a fraction of the same space. A FERRAM memory card or cartridge similar to those previously shown and discussed could easily satisfy both aircraft's memory requirements.

The E-2's entire 224 KByte memory requirement could be satisfied with 28 FMx 1608 8 Kbyte FRAMs. The EA-6B requires a total of 624 KBytes in three components. 30 FMx 1608 FRAMs could replace the current memory chips in both the display computer and the interface encoder (240 KByte total) and 48 FRAMs could fill the CMC 384 KByte memory requirement. A second option would be to use a FEM cartridge for the EA-6B CMC and the E-2 L-304 main memory requirements. This would allow the working memory to be increased to any desired capacity and convert the aircraft's programming procedure from a lengthy tape loading procedure to simply inserting a pre-programmed cartridge.

VI. CONCLUSIONS

FEM is still an infant technology. Because of this, FERRAM chip memory capacities are still very low. Ramtron's highest capacity chip using $150\mu^2$ memory cells is 64 Kbit / 8 KByte. In theory, the smallest achievable FEM cell size would be $4\mu^2$. It is reasonable to assume that as technology continues, FERRAM manufacturing technology will approach DRAM densities.

Previous radiation testing indicates that some ferroelectric test devices have failed as a result of irradiation. In review, three incidents of this were:

- 1987 Krysalis devices failed at 10 x 10 rads
- KNO^3 test devices failed at 0.5×10^6 rads
- Two PZT devices failed at 5×10^6 rads when the electrodes were shorted

There were many other tests indicating that PZT FEM devices exhibit radiation hardness between 5×10^6 and 16×10^6 rads. As ferroelectric technology progresses, standardized radiation hardness values for PZT FEM devices should be determined.

In December 1992, Ramtron Corporation announced that it is co-developing a four Mbit Ferroelectric memory with Hitachi. Symetrix is pursuing patents and licensing agreements for its Y1 Ferroelectric material. At the 1992 Fourth International Symposium on Integrated Ferroelectrics held in Monterey, CA, Olympus announced that they would be using 32 Mbit Ferroelectric devices in their HDTV products near the end of the year. These events indicate that commercial FEM products are imminent. The author feels that it is in the Department of Defense's best interest to continue participation in further FEM research.

In order to better define FEM characteristics the author recommends further study in the areas of:

- Testing FERRAMs made with Symetrix Y1 material (perhaps encouraging Ramtron to develop FRAMS using Y1)
- Performing a full battery of radiation and fatigue tests of Symetrix material when it becomes readily available
- Testing hundreds of working capacitors and FERRAMS to quantitatively determine their fatigue, radiation hardness and SEU parameters

This thesis discussed specific possible space and Naval aviation applications based on 8 KByte Ramtron FRAMs. Commercial products such as Intel flash memory, Targa flash memory cartridges and Irvine's stacked SRAM chips are examples of high memory capacity products that are available at this time. It is logical to assume that FEM devices could be developed with similar memory capacities, and would offer non-volatility, magnetic field insensitivity, low power consumption, high speed and perhaps become the "all-purpose" semiconductor memory.

APPENDIX A. SPECIFIC POINTS OF CONTACT

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(EA-6B technical representative)	Fax	805-388-2424
	5161 Verdugo Way	
	Camarillo, CA 93012	
CTS Corp	Darryl Starnes	612-536-0349
(Core Memory)	Fax	612-536-3622
	6900 Shady Oak Rd	
	Eden Prarie, MN 55344	
Cypress Semiconductor	Jay Legenhausen, Applications Engineer	408-943-4850
(SRAMs and EPROMs)	Fax	408-943-2741
	3901 North First St.	
	San Jose, CA 95134	
Databook Inc	Pete Robson, Sales Manager	716-889-4204
(PC memory card interface units)	Fax	716-889-2593
	10 Alder Bush	
	Rochester NY 14624	
Fujitsu Microelectronics	David Abney	408-922-9000
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	Fax	609-338-2741
	Government Communications Systems Department	
	Front and Cooper Sts. Bldg 2-4	
	Camden, NJ 08102	
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	Direct Marketing Organization	800-752-0900
	5301 Stevens Creek Blvd.	
	P.O. Box 58059, MS 51 LSG	
	Santa Clara, CA 95052-8059	

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	Roy Shimogake (Intelsat VI Engineer)	310-416-5887
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	Intel Literature	800-548-4725
	2700 San Thomas Expressway	
	Santa Clara, CA. 95051	
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	Building III	
	Costa Mesa, CA. 92626	
Lockheed Missile And Space	Norm Bennet	
(Hubble Space Telescope)	Space Telescope Flight Software Lead	408-742-3415
	ORG 6N-22, Bldg. 579	
	Lockheed Missile And Space	
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	Sunnyvale, CA 94088-3504	
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	JSC M/C CA4	
	Houston, Tx 77058	
Naval Air Test Center	LCDR Jim Clifton	301-737-3759
(E-2 Hawkeye)	Fax	301-862-9266
	VAW Dept. Code FW 701	
	Force Warfare ACFT Test Directorate	
	Naval Air Test Center	
	Patuxent River, MD 28670-5304	
Plasmon Data Systems	General Information	408-956-9400
(Optical disk systems)	Fax	408-956-9444
	1654 Centre Pointe Dr	
	Milipitas, Ca 95035	

Procom Technology	Mandi Wood	714-852-1000
(Optical, floptical, hard & floppy disks, and tape memory systems)	Fax	714-852-1221
	2181 Dupont Dr	
	Irvine, DA 92715	
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	3500 W. Balcones Center Dr.	
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	1 Annabel Lane, Suite 111	
	San Ramon, CA 94583	
Techmar	general information	216-349-0600
(Tape memory systems)	Fax	216-349-0851
	6225 Cochran Road	
	Solon, OH	
	44139-3377	

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